The Effects of Compositionally Graded Bases and Annealing on InGaP-GaAs HBTs Grown by MBE using a GaP Decomposition Source

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***Abstract*— InGaP-GaAs Single Heterojunction Bipolar Transistors (SHBTs) with a compositionally graded base have been successfully grown by Solid-Source Molecular Beam Epitaxy (SSMBE) using a GaP decomposition source. The device characteristics of InGaP-GaAs HBTs with $In_XGa_{1-X}As$ graded base $x : 0 \longrightarrow 0.1$ (MBE 1462) and $x : 0 \longrightarrow 0.05$ (MBE 1463) have been compared with conventional HBTs (MBE 1461) to investigate the optimum-grading profile. Additionally the effects of Rapid Thermal Processing (RTP) on Beryllium (Be)-doped $In_XGa_{1-X}As$ graded base layer lattice matched to GaAs have been investigated at different annealing temperatures. The average current gains of MBE 1461, MBE 1462, and MBE 1463 are 174, 342 and 321, respectively prior to annealing. It was founded that all the devices had no significant degrading Be out-diffusion in the base region up to annealing temperatures of 450^oC. To the best of our knowledge, these average currents are the highest value ever reported in InGaP-GaAs HBTs with a compositionally graded base and establish a new benchmark for high gain InGaP-GaAs HBTs.**

I. Introduction

The InGaP-GaAs Heterojunction Bipolar Transistor (HBT) material system has shown better performances compared with the AlGaAs-GaAs HBT material system due to its favorable band line-up, relatively inert surface [1]-[2], and the high etching selectivity between InGaP and GaAs. In addition its low noise performances and its high frequency capabilities make it an ideal candidate for wireless and high-speed devices [3]-[4].

In most applications, it is desirable to have a high current gain and in practice there are two methods to improve this factor in HBTs. One is to enhance the emitter injection efficiency (β) and the other is to improve the base transport factor. Generally the former can be achieved using a higher valence band discontinuity, ΔE_V or/and an undoped spacer layer while the latter can be obtained using a thin and highly doped base or/and, a compositionally graded base or a graded doping base. From these points of view, there are two significant difficulties concerning the base transport factor in HBTs. One is the base ohmic contact due to the very thin layer used $(< 1000\mathring{A})$ and the other is the base dopant (p-type) stability. Specifically the redistribution of the base dopants is one important reason, which can severely degrade the device characteristics due to the (electrical) junction shift at the emitter-base junction, resulting in the increase of the base transit time and possible carrier recombination. Therefore the stability of p-dopants is a critical issue in the performances of HBTs. As a p-type dopant for use in MBE, Be is widely used because of its unity sticking coefficient and low diffusion coefficient compared with other candidates such as Ge, Zn, and Mn [5]. Additionally Be had been proved as a useful acceptor of GaAs in the MBE growth because of its excellent mobility and possibility of high doping level [6] even though in the case of AlGaAs-GaAs Be-doped HBTs there is rapid dopant redistribution because of the $> 600^oC$ growth temperature needed for optimal growth of the AlGaAs emitter. An alternative is to use Carbon due to its high solid solubility and low diffusivity $(< 10^{14} cm^2 s^{-1}$ at 900^oC in GaAs) [7]-[8]. However the doping concentration and the p-type nature of Carbon is a very strong function of the growth condition used and processes such as post-growth annealing (during device fabrication for example) can result in n-type doping, limited doping levels, or carbon-related defects occurrence [9].

In these studies we have used Be as the p-type dopant in our HBT devices .The key observation is that heavily doped base never sees growth temperatures in excess of 500^oC since the InGaP emitter is grown at 450^oC. By growing the whole structures well below conventional MBE growth temperatures we are able to confine the Be-dopant and as a consequence achieved thermal stability at annealing temperatures as high as 450^oC.

In this paper, we focus on the improvement of the current gain using compositionally graded and heavily doped $In_XGa_{1-X}As$ bases. The effects of annealing on InGaP-GaAs HBTs with $In_XGa_{1-X}As$ graded bases have been investigated. From the differences in the annealing temperatures, we have gained an insight into the effect of Be out-diffusion. From comparison of conventional and compositionally graded base InGaP-GaAs HBTs, the high thermal stability of Be was found in both the conventional InGaP-GaAs HBTs and InGaP-GaAs with a compositionally graded $In_{0.05}Ga_{0.95}As$ base.

II. Experiment

All the structures were grown on (100) oriented semi-insulating GaAs substrates. The epitaxial structure consists of an n^{++}-InGaAs none-alloyed ohmic (50nm, $1 \times 10^{19}\ cm^{-3}$), an n^{++}-$In_XGa_{1-X}As$ strain relieve layer (40nm, $1 \times 10^{19}\ cm^{-3}$, $0 \longrightarrow 0.5$), an n^{++}-GaAs ohmic (50nm, $7 \times 10^{18}\ cm^{-3}$), an n-GaAs emitter I (150nm, $5 \times 10^{17}\ cm^{-3}$), an n-InGaP emitter II (40nm, $5 \times 10^{17}\ cm^{-3}$), an *intrinsic*-GaAs spacer (3nm), a p^{++}-$In_XGa_{1-X}As$ base (102nm, $2.5 \times$

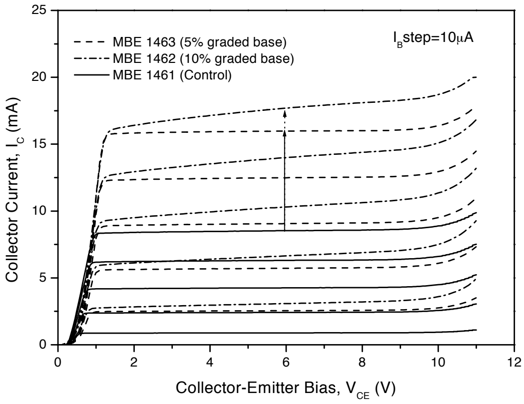

Fig. 1. I-V curves for InGaP-GaAs HBTs without annealing

10^{19} cm^{-3}, $0 \longrightarrow 0,\ 0.05\ \&\ 0.1$), an n^{-}-GaAs collector (700nm, 1×10^{16} cm^{-3}) and an n^{++}-GaAs sub-collector (700nm, 7×10^{18} cm^{-3}). The $In_{0.5}Ga_{0.5}P$ emitter was grown using a GaP decomposition source whose operational characteristics has been reported elsewhere [10]. In brief, the GaP source generates a pure beam of P_2 (phosphorous dimers) which has a higher sticking coefficient compared with P_4 (phosphorous tetramers) leading to not only a very safe source for use in conventional MBE systems but also permits the growth of extremely high quality materials at the low growth temperature of $\sim 450^oC$. The epi-layers were grown under conditions of exact stoichiometric beams of the group III and V elements. The growth rate was $1\mu m/h$ for both GaAs and InGaP layers and the substrate temperatures were 500^oC and 450^oC for the base and emitter regions, respectively. The collector was designed to have a moderately low doped region ($\sim 1 \times 10^{16} cm^{-3}$) and this resulted in a collector-base breakdown voltage in excess of 24V. Indium was added to generate the compositionally graded base, resulting in an induced built-in potential. The base doping level ($\sim 2.5 \times 10^{-19} cm^{-3}$) was very high in the context of Be-doping of GaAs. An undoped spacer of $\sim 30\mathring{A}$ was inserted between the emitter and the base and whose main role was to decrease the spike at the conduction band interface. The emitter region was terminated with a heavily doped, graded $In_{0.5}Ga_{0.5}As$ non-alloyed contact region.

After epitaxial growth, a chemical wet etching process was applied to define a 60×60 μm^2 emitter area. The initial etching process was H_3PO_4 : H_2O_2 : H_2O (3:1:50 by volume) mixture to remove the cap and the emitter I layer. Pure HCl was used to etch the $In_{0.5}Ga_{0.5}P$ layer to define the emitter region and the base region. After the first etching, the sub-collector was etched using the same solution. The ohmic contacts were then fabricated through conventional evaporation and lift-off processes. AuGeNi alloyed metal was used for the sub-collector ohmic contact and was then annealed under N_2 ambient in a rapid thermal annealer. Non-alloyed Ti/Au metal was applied for the emitter and the base ohmic contacts. To investigate Be out-diffusion, pieces of samples from each wafer were annealed for 15 minutes at $400^oC, 450^oC$, and 500^oC using the RTP system.

III. Results and Discussion

Fig. 1 shows the I-V characteristics in the common-emitter mode for all the three different InGaP-GaAs HBTs prior to thermal annealing. The average current gains of MBE 1461 (Control), MBE 1462 (10% graded) and MBE 1463 (5% graded) are 174, 342 and 321, respectively. These current gains are the highest ever reported in the InGaP-GaAs material system compared with devices having similar base sheet resistance [11] and either grown by MOCVD [12] or MBE [13]. We believe these results from the low growth temperature techniques used in here and which include stoichiometric growth for both the arsenides and the phosphides. The stoichiometric low growth temperature ($\sim 450^oC$) growth used in here also makes it possible to lower defects and Be out-diffusion during the epitaxial layer growths [14]-[15].

The compositionally graded base improves the built-in potential to $\sim 9.6\ kV/cm$ and $\sim 5\ kV/cm$ for the 10% graded base sample (MBE 1462) and 5% graded base sample (MBE 1463), respectively. These induced built-in potentials force the electrons to move faster and also have the effect of greatly reducing the recombination with holes in the base region (See Fig. 2). From this effect, the average current gains of the compositionally graded base HBTs are about twice that of the conventional InGaP-GaAs HBTs. However the electrons have much higher energy due to the higher induced electric field in MBE 1462, which might produce more hot electrons with shorter momentum relaxation times in the base and collector regions. This effect leads to impact ionization effect and results in the low breakdown voltage for the 10% compositionally graded base HBTs (See Fig. 1).

For the control sample it can be seen that the gain is not constant with applied base current, I_B. The gain is an increasing function of the applied I_B in agreement with conventional InGaP-GaAs HBT characteristics. The reason why the gain is not constant for each applied I_B ($10\mu A/step$) is most likely due to surface states or traps from the extrinsic base region and the collector region. These surface states act as trap-levels in the energy band and thus electrons that travel through these regions are trapped by these states. From these results, we can suggest that the built-in field in the graded bases is very effective in suppression carrier recombination at the exposed GaAs surface and thus the induced electric field lead to constant gains even at the low applied I_B biases as shown in Fig. 2 where The ideality factors of the collector current, n_C of MBE 1461, MBE 1462 and MBE 1463 are 1.04, 1.07 and 1.01, respectively.

These results means that the effective height of ΔE_C is very small indeed at applied biases and the epi-layer quality of the base is very high. The ideality factors of the base current, n_B of MBE 1461, MBE 1462 and MBE 1463 are 1.68, 1.39 and 1.52, respectively. The high n_B indicates that the space charge region and the extrinsic base surface are major factors, which degrade the device characteristics due to the unpassivated surface region used in these experiments. However n_B of MBE 1462 is lower than those of MBE 1461 and MBE 1463. we can therefore deduce that the increase of the induced built-in potential by compositional grading reduces the probability of making a recombination current in the extrinsic base region and Indium makes it possible to lessen the native defects in the GaAs base.

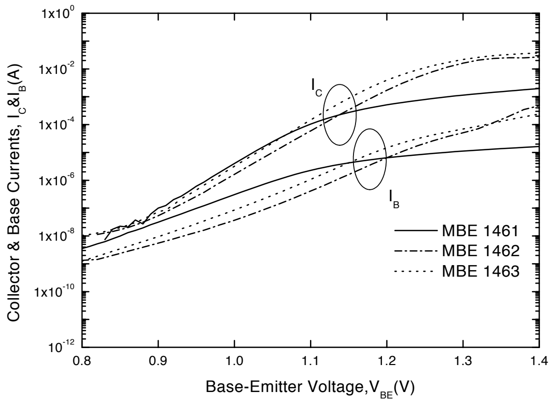

Fig. 2. Gummel Plots for InGaP-GaAs HBTs without annealing

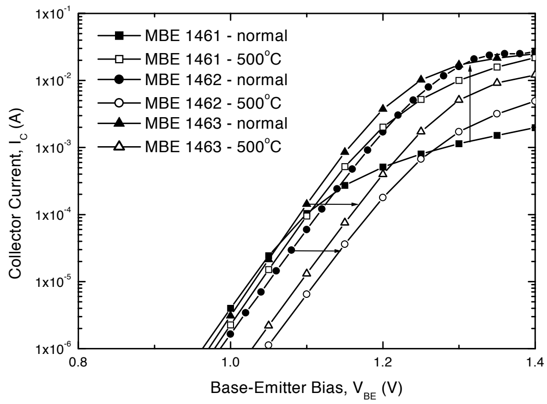

Fig. 4. The comparison of I_C-V_{BE} curves with the annealing temperature at 500^oC

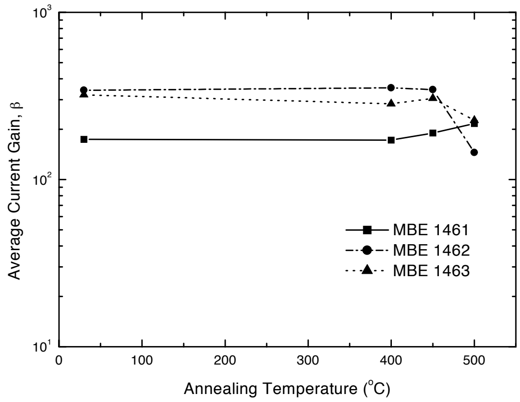

Fig. 3. The variation of Gains with the annealing temperatures for InGaP-GaAs HBTs

When the structures were subjected to annealing (and then HBT fabricated), the average current gains increase by 24% up to 500^oC for the control sample (See Fig. 3). These current gains of the control sample are much higher when compared with Carbon-doped InGaP-GaAs HBTs reported by Yang et al [9]. Their structures had twice our doping $(5.5 \times 10^{19}\ cm^{-3})$ however the sheet resistances are comparable which suggests that the carbon doped devices had half the hole mobilities we measure in ours ($\sim 90\ cm^2/Vs$). The annealing process thus helps in stabilizing the InGaP-GaAs HBT. Moreover there are no negative differential resistances (NDRs) in the control sample throughout 500^oC. These results mean that $\Delta E_g{}^{\Gamma-L}$ separation is high enough to prevent the onset of intervalley scattering. However the offset voltage increases somewhat at 500^oC. The offset voltage increase is believed to be the out-diffusion of Be and the degradation of the interface between the emitter and the base.

The compositionally graded structures behaved differently. For the 10% graded base sample, the current gain is constant at $\sim$ 350 up to 450^oC and drops to $\sim$ 145 at 500^oC probably because of Be out-diffusion and the extension of the emitter-base depletion layer. There is a pronounced NDR after annealing at 500^oC, as well. This means that there is shrinkage in the separation between Γ-valley and L-valley. This sample also had the largest amount of indium in it and may thus suffer from dislocation generation during annealing.

The induced electric field for the 5% graded base sample (MBE 1463) is maintained after annealing up to 500^oC, resulting in a lower drop of the current gain and n_C compared with the 10% graded base sample (MBE 1462). Its offset voltage was improved with temperature up to 450^oC. These results would imply that the heat treatment has a beneficial effect in reducing defects and stabilizing the devices. Consequently it appears that the high stabilization of Be-dopants in the 5% graded base sample by use of the low growth temperature schedule used here are the most likely reasons for the high gain improvement.

Fig. 4 compares the gummel plots of the three different devices as a function of annealing temperature. For the compositionally graded base devices there is a dramatic enhancement in the collector current from 1.2 V_{BE} which indicates that the induced built-in potential reduces the recombination probability in the base region. However the Be out-diffusion shifts the collector current seriously to the right hand side in the compositionally graded base HBTs when compared with the control sample (MBE 1461) at 500^oC. The collector current drop in the graded base devices (MBE 1462 and MBE 1463) is believed to be due to the expansion of the depletion layer between the emitter and the base due to the Be out-diffusion, resulting in the large n_C and n_B. However there is no significant degradation up to 500^oC for the control sample (MBE 1461). The variation of collector currents at high biases $(V_{BE} > 1.2V)$ probably comes from the different contact resistances.

Fig. 5 depicts information about the material quality and the device fabrication and describes the effect of Indium mole fraction on R_{sh} and n_C. The R_{sh}s in the study are much lower and show considerable improvement compared with [11] and [12]. From TLM measurements the R_{sh}s are 240 $\Omega/sq.$, 209 $\Omega/sq.$ and 184 $\Omega/sq.$ for the control, 10% and 5% graded base samples, respectively before annealing. From these results, the addition of Indium can be seen to improve the induced built-in potential and reduce the resident defects in GaAs layer at 5% Indium mole fraction. However the slight out-diffusion of Be can be observed in MBE 1462 after annealing at 500^oC. In MBE 1462, both R_{sh} and n_C increase. A calculation based on pseudomorphic critical

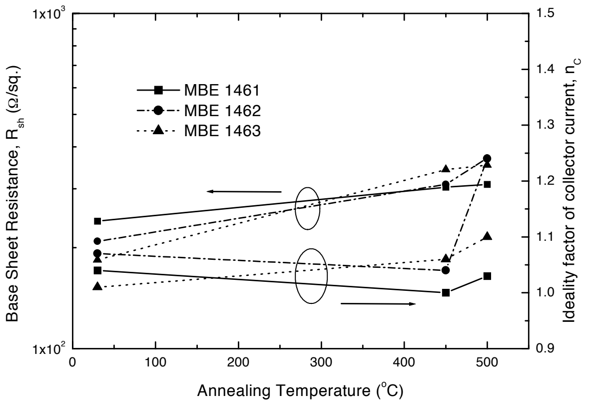

Fig. 5. The base sheet resistances, R_{sh} and the ideality factor of the collector current, n$_C$ with the annealing temperatures

thickness allowable, points to the fact that the $1020\ \AA$ base thickness would probably exceed the critical thickness for the 10% graded base layer. Therefore we can observe $\sim$ 60% increase in n_B and $\sim$ 16% increase in n_C at 500^oC compared with the non-annealed HBTs. The higher ideality factors may come from the degradation of the interface between the emitter and the base due to the Be out-diffusion. However the n_Cs maintain a unity value throughout 500^oC in MBE 1461. Therefore the effect of Be out-diffusion could be negligible in spite of the heavily doped base.

We can therefore surmise that together with Fig. 4 and Fig. 5. the results suggest that there is no significant drop up to 500^oC in MBE 1461 and MBE 1463 which imply that the degradation of the emitter-base junction and the dopant out-diffusion are negligible. However MBE 1462 has significant increase in its n_C and R_{sh} at 500^oC which means that this annealing temperature generated Be out-diffusion which corrupted the emitter-base junction.

IV. Conclusion

We have shown that InGaP-GaAs HBTs with a compositionally graded In$_X$Ga$_{1-X}$As base can considerably improve the device characteristics. Before annealing, the device parameters such as β, R_{sh}, base-emitter turn-on voltage $(V_{BE\ on})$ and n_C indicate that Be out-diffusion was negligible during MBE growth in spite of the higher Be doping in the base. The values of the common emitter current gain are the highest ever reported in the InGaP-GaAs HBT system.

From a comparative study, MBE 1463 has excellent performances as compared with either MBE 1461 or MBE 1462 up to 450^oC. These results means that the interface between emitter and base had no significant degradation by Be out-diffusion and the induced built-in potential had a major factor in improving the current gain up to the annealing temperature of 450^oC. However for compositionally grading of 10% there is evidence that both structural defects and Be out-diffusion are responsible for the drop in the DC current gain and drift in the base sheet resistance, R_{sh} especially at 500^oC. The 5% graded base and the control sample maintained their high DC current gains, low base sheet resistances, unity n_Cs, and the high breakdown voltages of over 11 V throughout 500^oC. We believe that the improvement of the current gains and the stability of Be-dopants in InGaP-GaAs HBTs mainly comes from the stoichiometric low temperature growth ($\sim 450^oC$) schedule coupled with the use of a GaP decomposition source, the low recombination probability in the base region by the induced built-in potential, and the reduction of the native defects in GaAs layer by the increase of Indium mole fraction.

These results have demonstrated that InGaP-GaAs HBTs with In$_{0.05}$Ga$_{0.95}$As graded base and conventional InGaP-GaAs HBTs are promising for microwave power amplifiers.

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